Computers & Operations Research 61 (2015) 18–30

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

A maritime inventory routing problem with stochastic sailing and port times

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ARTICLE INFO

Available online 20 February 2015

Keywords:
Stochastic programming
Maritime transportation
Inventory routing
Uncertainty
L-shaped method
Sample average approximation
Travel time
Service time

ABSTRACT

This paper describes a stochastic short sea shipping problem where a company is responsible for both the distribution of oil products between islands and the inventory management of those products at consumption storage tanks located at ports. In general, ship routing and scheduling is associated with uncertainty in weather conditions and unpredictable waiting times at ports. In this work, both sailing times and port times are considered to be stochastic parameters. A two-stage stochastic programming model with recourse is presented where the first stage consists of routing, loading and unloading decisions, and the second stage consists of scheduling and inventory decisions. The model is solved using a decomposition approach similar to an L-shaped algorithm where optimality cuts are added dynamically, and this solution process is embedded within the sample average approximation method. A computational study based on real-world instances is presented.

1. Introduction

Maritime transportation is characterized by high levels of uncertainty. In practice, operational plans are often adjusted due to factors such as changing weather conditions, port congestions, or mechanical problems at port. A plan that minimizes the transportation and port costs based on expected sailing and port times may not necessarily be good, as it does not account for the consequences resulting from delays. Hence, in most practical situations it will be beneficial to consider the possibility of delays when trying to minimize costs.

In this paper we study a maritime inventory routing problem occurring at the archipelago of Cape Verde. A deterministic variant of this problem was solved to optimality in [3] for short time horizons. Heuristics for the same problem with time horizons up to 6 months were developed in [4]. The deterministic methods assume known and fixed sailing times, but the planner needs to face the uncertainty associated with the ships sailing between ports. This may somehow be circumvented by the inclusion of safety stocks or by artificially increasing the sailing times to compensate for delays. The ports are used by several independent shipping companies, and limited co-ordination between the various operators can result in heavy port congestion. This may come from limited capacities in the inner port area, at berths, and of pipes and other important equipment for performing the (un)loading operations. Here, we explicitly consider uncertainty in both sailing times between ports and waiting times at ports.

In the problem considered, a heterogeneous fleet of ships is transporting several oil products between supply and consumption storage tanks. These tanks are located close to or at ports, and a particular port might have both supply and consumption storage tanks for various products. Inventory management is only considered for the consumption storage tanks because these tanks have limited capacity, and it is important that these tanks do not run empty. In contrast, unlimited capacity and supply of products are assumed for the supply storage tanks. By taking the uncertain sailing times and port waiting times into account, the objective of the planning is to design cost efficient ship routes and schedules including determining the number of visits to each port and the (un)loading quantities at each visit.

The purpose of this paper is to describe a stochastic programming model with recourse where the routes and the quantities to load and unload must be fixed *a priori*, that is, before actual values of the uncertain parameters are revealed, while the schedule of the loading and unloading operations can be adjusted according to the observed sailing and port times. In addition, the paper contributes with a solution method that combines the use of the sample average approximation method with a decomposition procedure resembling an L-shaped method [11,17]. For a given set of scenarios, the corresponding two-stage model is solved to obtain a candidate solution. This is repeated for several different sets of scenarios to

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http://dx.doi.org/10.1016/j.cor.2015.01.008
0305-0548/

obtain several candidate solutions. To choose the best solution, these candidate solutions are evaluated for a larger and independent set of scenarios. To solve the two-stage model for a given set of scenarios, the problem is decomposed into a master problem and one subproblem for each scenario, where the second-stage decisions are considered in the subproblems. We show that feasibility of the second stage is always guaranteed when the solution obtained for the first-stage is feasible. Then we show how to derive optimality cuts from the subproblems that are added dynamically to the master problem. As far as we know, this paper describes the first stochastic programming model and approach for solving a maritime inventory routing problem with uncertain sailing and port waiting times.

The remainder of this paper is organized as follows. In Section 2 we describe the real problem. Relevant literature is reviewed in Section 3. Then, in Section 4 we present a scenario-based mathematical formulation for the problem. The solution approach based on decomposing the problem is discussed in Section 5. In Section 6 we describe how the stochastic sailing and port times have been modeled, and how scenarios have been generated. Section 7 contains a computational study based on real-world instances, and in Section 8 we present the main conclusions of this work.

2. Problem description

In Cape Verde, fuel oil products are imported and delivered to two specific islands and stored in large supply storage tanks, see Fig. 1. From these islands, fuel oil products are distributed among all inhabited islands using a small heterogeneous fleet of ships. The two circled islands in Fig. 1 are served by a different ship and may therefore be disregarded. Products are stored in separate consumption storage tanks with limited capacity. Some ports have both supply tanks for some products and consumption tanks for other products. As the capacities of the supply tanks are very large compared to the total consumption over the planning horizon, the inventory aspects for these tanks can be ignored. The driving force in the problem is the need for fuel oil products in the consumption storage tanks. If the demand is not satisfied, the backlogged demand will be penalized by a cost.

Not all islands consume all products. Consumption rates are assumed to be constant over the time horizon. Each port can receive at most one ship at a time, and in some ports there exists a minimum time interval between the departure of one ship and the arrival of the next ship.

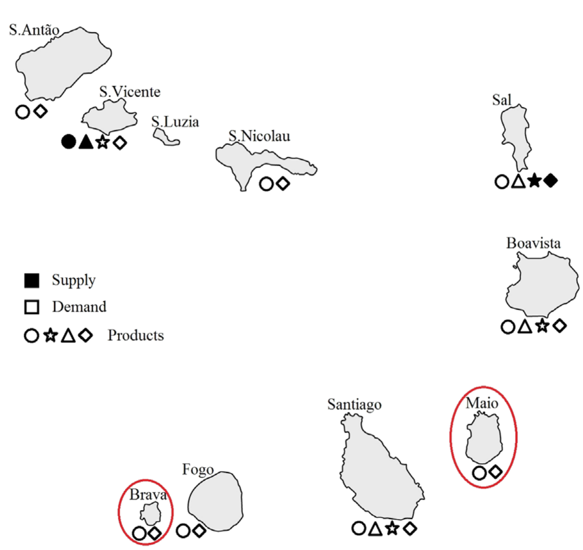

Fig. 1. Supply and demand for fuel oil products at several islands in Cape Verde.

Each ship has a specified capacity, fixed speed, and cost structure. The cargo hold of each ship is separated into several cargo tanks. The products cannot be mixed, so we assume that the ships have dedicated tanks for the particular products. The ships are either sailing, waiting outside a port or operating. Here, operating is the common term for loading and unloading.

At port, we consider set-up times for the coupling and decoupling of pipes and operation times which depend on the amount loaded or unloaded. Minimum and maximum unloading quantities can be derived based on properties of the ships and the inventories. The maximum unloading quantity is imposed by the consumption tank capacity and by the ship cargo tank capacity.

The traveling times depend upon the weather conditions and are considered stochastic. The uncertain time parameter at port is mainly related to the time from arrival to start of operation. Hence, a specified waiting time before start of service is defined as stochastic, while the operation times are deterministic.

The inter-island distribution plan consists of routes and schedules for the fleet of ships, and describes the number of visits to each port and the quantity of each product to be loaded or unloaded at each port visit. This plan must satisfy the capacities of the ships and consumption storage tanks while minimizing the sailing and port costs as well as the expected penalty costs of backlogged demand. There is great flexibility in the route pattern of a ship, such that a ship may load in several successive ports as well as performing unloading operations in succession. The quantities loaded or unloaded are variable as well as the number of visits at each port. The problem described here will be referred to as a *stochastic maritime inventory routing problem* (SMIRP), and a scenario-based stochastic programming model for the problem is given in Section 4.

3. Literature review

The amount of literature on maritime transportation optimization has increased steadily over the last decades, as evidenced through the recent survey in [13]. Despite being a transportation mode that is heavily influenced by uncertainty, most of the literature on maritime routing and scheduling involves solving static and deterministic problem variants. However, some contributions exist, and we describe some that are considering problems close to the stochastic maritime inventory routing problem of this paper.

An inventory routing problem with uncertain demands and sailing times was solved heuristically by Cheng and Duran [12]. Rakke et al. [28] and Sherali and Al-Yakoob [30,31] introduced penalty functions for deviating from the customer contracts and the inventory limits, respectively. Christiansen and Nygreen [14] introduced soft inventory levels to handle uncertainties in sailing and port times, and these levels were transformed into soft time windows.

Agra et al. [5] solved a full-load ship routing and scheduling problem with uncertain travel times using robust optimization. Halvorsen-Weare and Fagerholt [15] considered weather conditions that affect both sailing speeds and the loading and unloading operations for supply vessels servicing offshore installations, and proposed various heuristic strategies to achieve robust weekly voyages and schedules. Heuristic strategies for obtaining robust solutions with uncertain sailing times were also discussed by Halvorsen-Weare et al. [16] for the delivery of liquefied natural gas. None of the aforementioned papers described the use of stochastic programming to model uncertain sailing and port times.

Considering the literature on non-maritime transportation optimization, some researchers have developed models and exact solution methods for vehicle routing problems (VRPs) with uncertain travel times. Considering a VRP with stochastic travel times and service